Thermo-nuclear X-ray bursts from Ultra-compact binaries

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The Physics of
ULTRACOMPACT STELLAR BINARIES
+
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=
UCSB!

UCSBs

source	P_{orb}(min)	T/P	bursts?	Ne/O excess	Suggested donor
4U 1820-30	11	P	Y	?	He
A 1850-08	21	T	Y	Y	C-O
4U 1626-67	42	P	N	Y	C-O
XTE J1751-305	42	T	N?	N	He
XTE J0929-314	44	T	N	N	He
4U 1916-05	50	P	Y	?	He?
MX 0513-40	$\lesssim$80	T	Y	?	?
4U 0614+091	$\lesssim$80	P	Y	Y	C-O
2S 0918-549	$\lesssim$80	P	Y	Y	C-O
4U 1543-624	$\lesssim$80	P	N	Y	C-O
4U 1822-00	$\lesssim$80	P	N	?	?
H1825-331	55 or 132?	P	Y	?	?
XB 1745-25	25-240?	T	Y	?	?

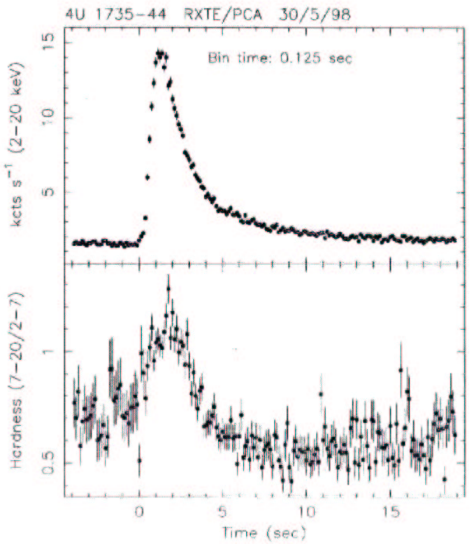
- $P_{orb} \lesssim 80$ min → H-depleted donors (Nelson et al. 1986)
- Ne/O excess – see Juett et al. 2001
  Juett & Chakrabarty 2002

→ X-ray bursts as tracer of donor composition

Observational properties of X-ray bursts

- Fast rise (~1–10 sec), exponential decay (few sec to mins)
- Spectral softening during decay (due to cooling of neutron star surface)
- Burst emission best described by black-body radiation with temperatures of T~1–4×10^7 K (kT~1–3 keV) and radius of ~10 km
- Total energy released is typically ~10^{39}–10^{40} erg

⇒ Thermo-nuclear runaway on a neutron star of H/He

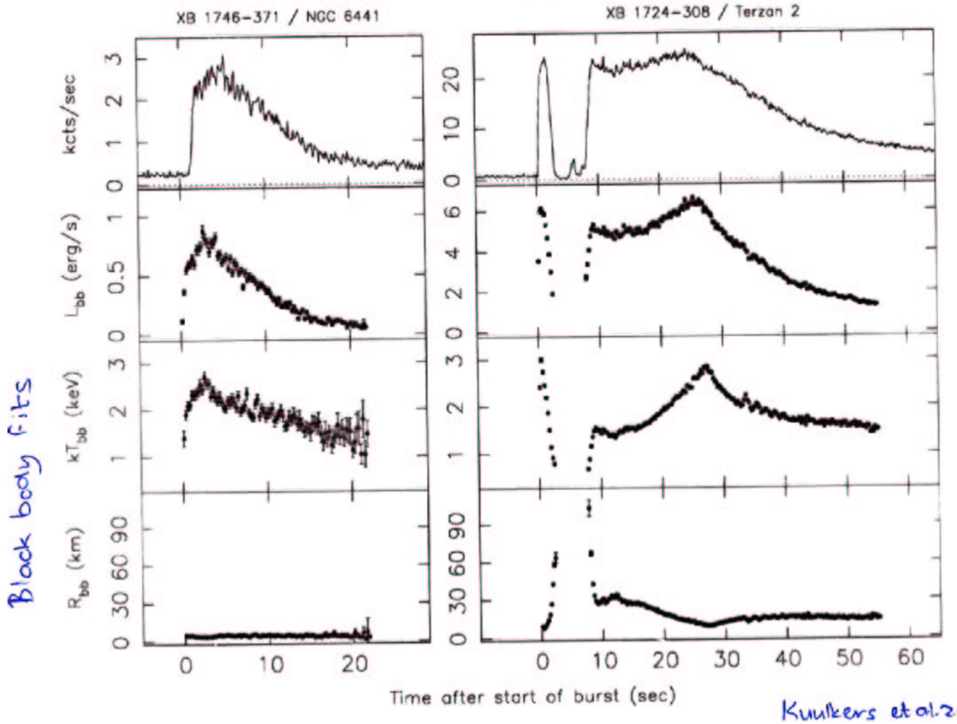


- Back-of-the envelope calculation:

E_{burst} ~ 10^{39} erg;
$E_{nuclear}$ ~1 MeV/nucleon
(~10^{18} erg/g)
⇒ fuel ΔM ~ 10^{21} g;
for $\dot{M}$ ~10^{-10} to 10^{-9} $M_\odot$/yr
⇒ t_{recur} ~ hrs–days

Normal X-ray bursts (continued)

radius expansion!



Kuulkers et al.2002

- **Left**: Typical type I X-ray burst
  - Heating during rise, cooling during decay; radius constant
- **Right**: If burst luminosity reaches Eddington limit ⇒ Radius expansion type I burst
  - $L_{\rm burst} = 4\pi R^2 \sigma T^4$; when $L_{\rm burst} = L_{\rm Edd}$ ⇒ If R increases, T decreases, while $L_{\rm burst} \simeq$ constant
  - If R big, radiation shifts to UV (because T very low) ⇒ drop in X-ray light curve

Regimes of mass accretion rates

X-ray burst theory predicts 3 different regimes in mass accretion rate ($\dot{M}$) (e.g. Fujimoto et al. 1981, Fushiki & Lamb 1987).

H/He

1) low accretion rates;
$10^{-14}\,M_\odot\,yr^{-1} \lesssim \dot{M} \lesssim 2 \times 10^{-10}\,M_\odot\,yr^{-1}$:
mixed H/He burning triggered by thermally unstable H ignition

2) intermediate accretion rates;
$2 \times 10^{-10}\,M_\odot\,yr^{-1} \lesssim \dot{M} \lesssim 4\text{–}11 \times 10^{-10}\,M_\odot\,yr^{-1}$:
pure He shell ignition after steady H burning

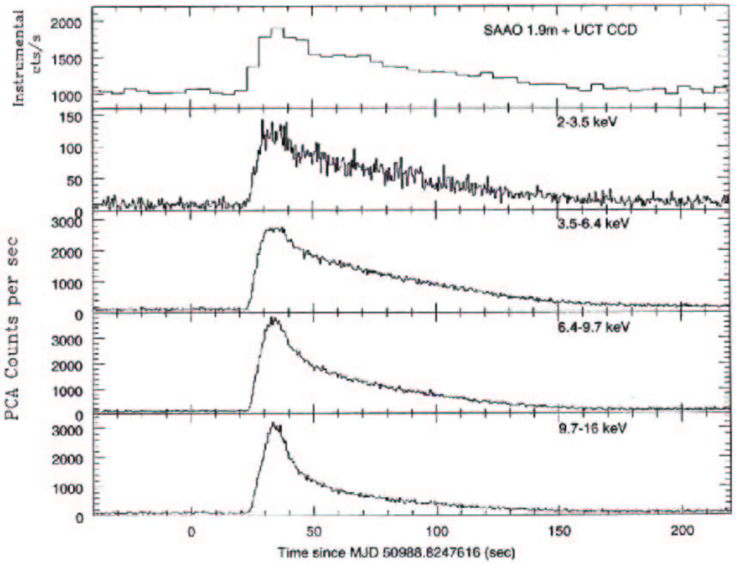
3) high accretion rates;
$4\text{–}11 \times 10^{-10}\,M_\odot\,yr^{-1} \lesssim \dot{M} \lesssim 2 \times 10^{-8}\,M_\odot\,yr^{-1}$:
mixed H/He burning triggered by thermally unstable He ignition

- During pure helium flashes the fuel is burned rapidly; they last only ~5-30 s
- Bursts with unstable mixed H/He burning release their energies on a longer, 10–100 s, timescale, due to the long series of β decays in the rp-process

→ length of X-ray burst
= trace of composition!

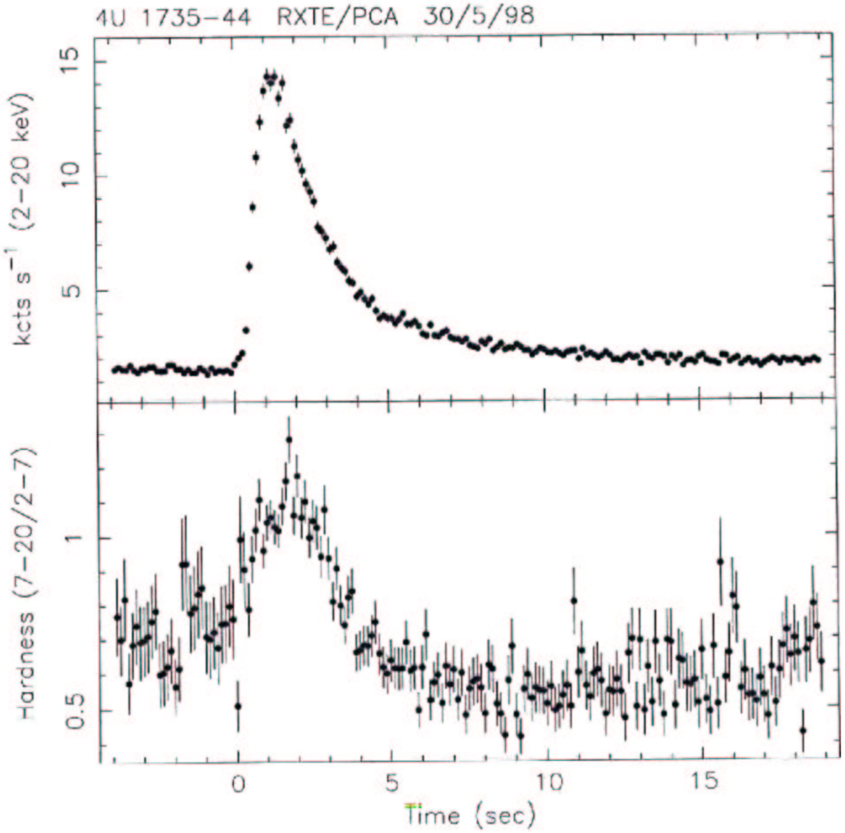
Low mass accretion rates:
GS 1826−24 (Kong et al. 1999)

- Slow rise (~10 sec) ⇒ H ignition
- Long decay ⇒ unstable mixed H/He burning through rp-process



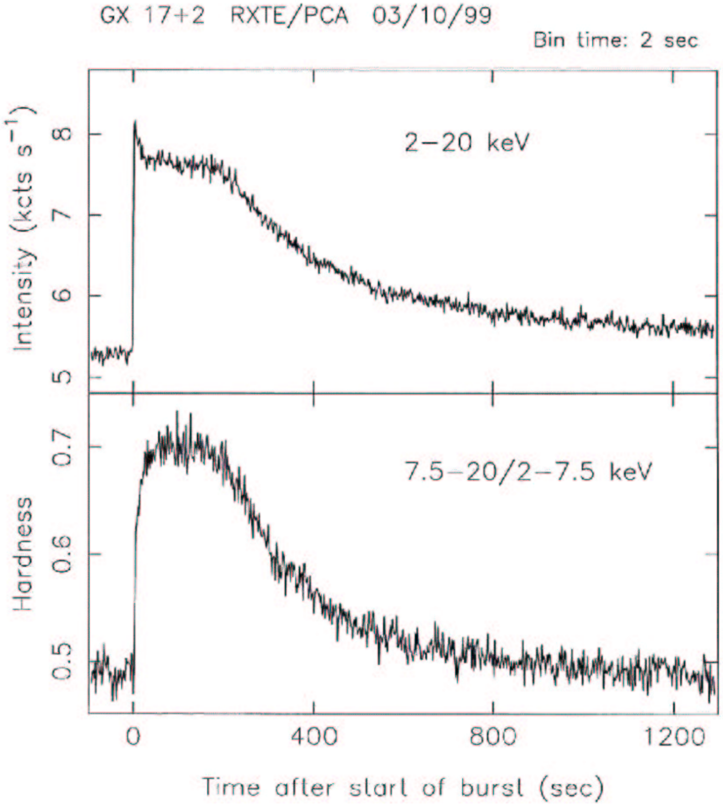
Medium mass accretion rates:
4U 1735−44

- Fast rise (~1 sec) + fast decay (<10 sec) ⇒ pure He flash



High mass accretion rates:
GX 17+2 (Kuulkers et al. 2002)

- Fast rise (~1 sec) ⇒ He ignition
- Long decay ⇒ unstable mixed H/He burning through rp-process



- X-ray bursts as tracers of donor composition
  - radius expansion bursts:

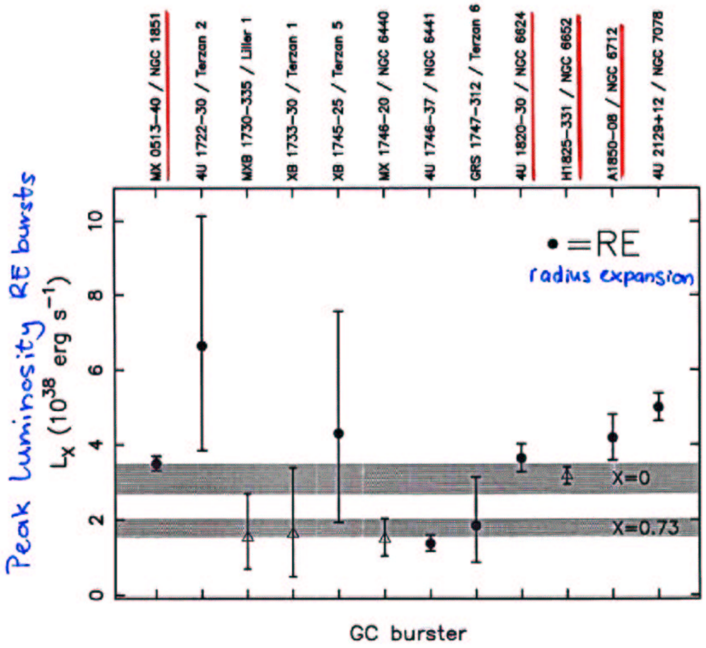
    $L_{peak} - L_{Edd,He} \triangleq 1.7\, L_{Edd,H}$
  - duration (or decay time) burst:

    $t_{burst} \gtrsim 30$ sec ⇒ H/He

    $t_{burst} \lesssim 30$ sec ⇒ He or H/He
  - $t_{burst} \lesssim$ hr ⇒ He or H/He

    → rule out C-O donors ?

Empirical standard candles (2)

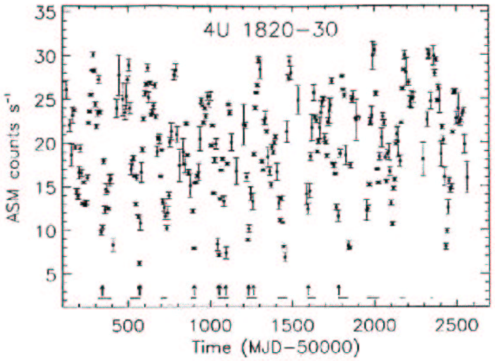


- RE bursts: $L_X = 3.79 \pm 0.15 \times 10^{38}$ erg/s $= L_{Edd}$ for H-poor material (excluding 4U 1746−37)

Kuulkers et al. 2002

X-ray bursters in Globular Clusters

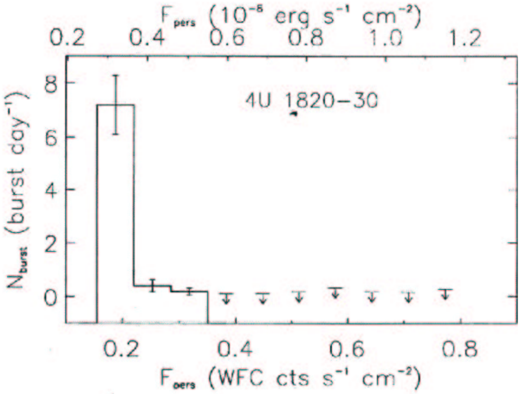
— distance known independently

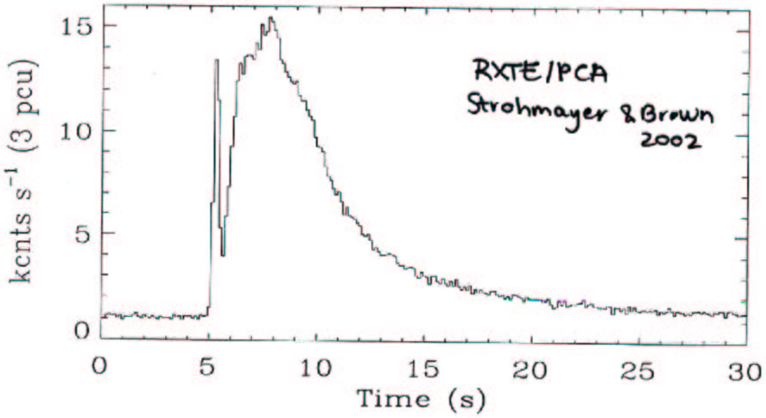


BeppoSAX / WFC

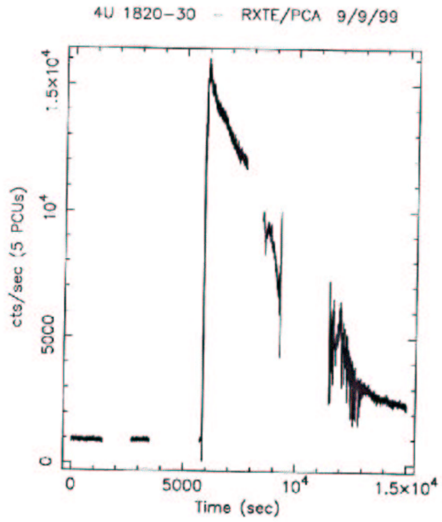
Cornelisse etal. 2003

P_{orb} = 11 min





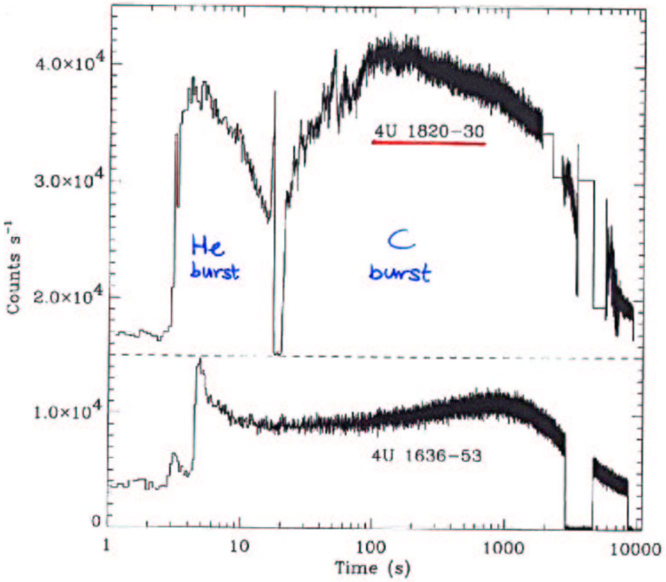
RXTE/PCA
Strohmayer & Brown
2002



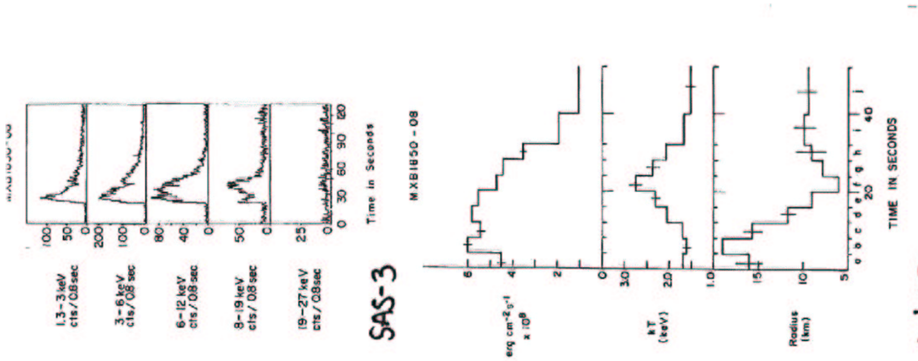
RXTE/PCA

- 4U 1820−30: $\tau_{exp} \sim 1$ hr
- Energy release: $\sim 10^{42}$ erg

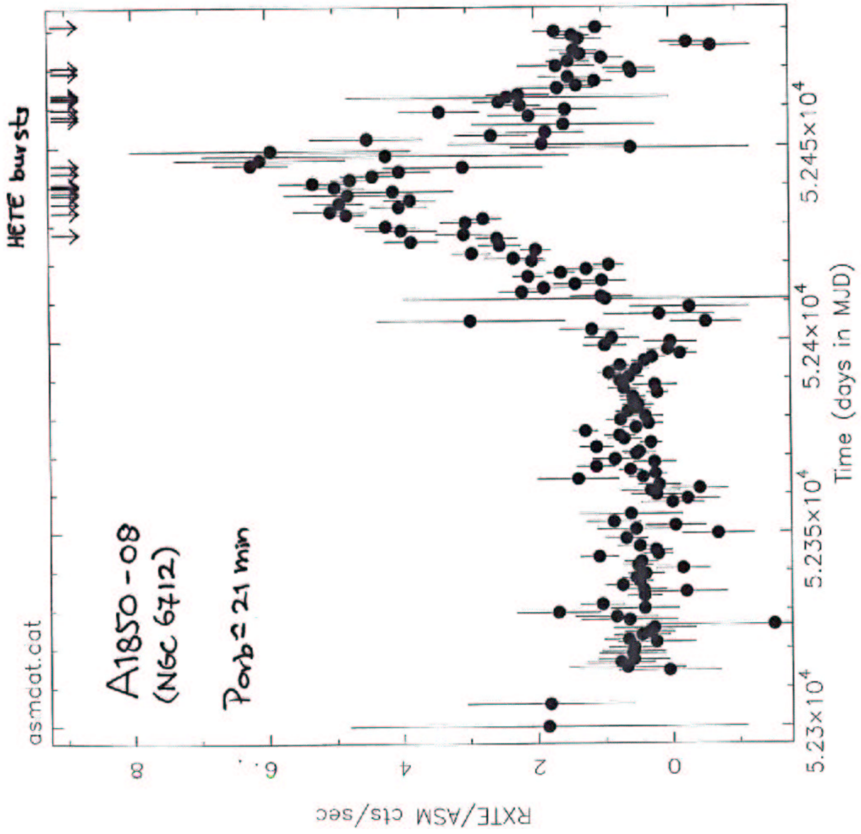
→ unstable C burning

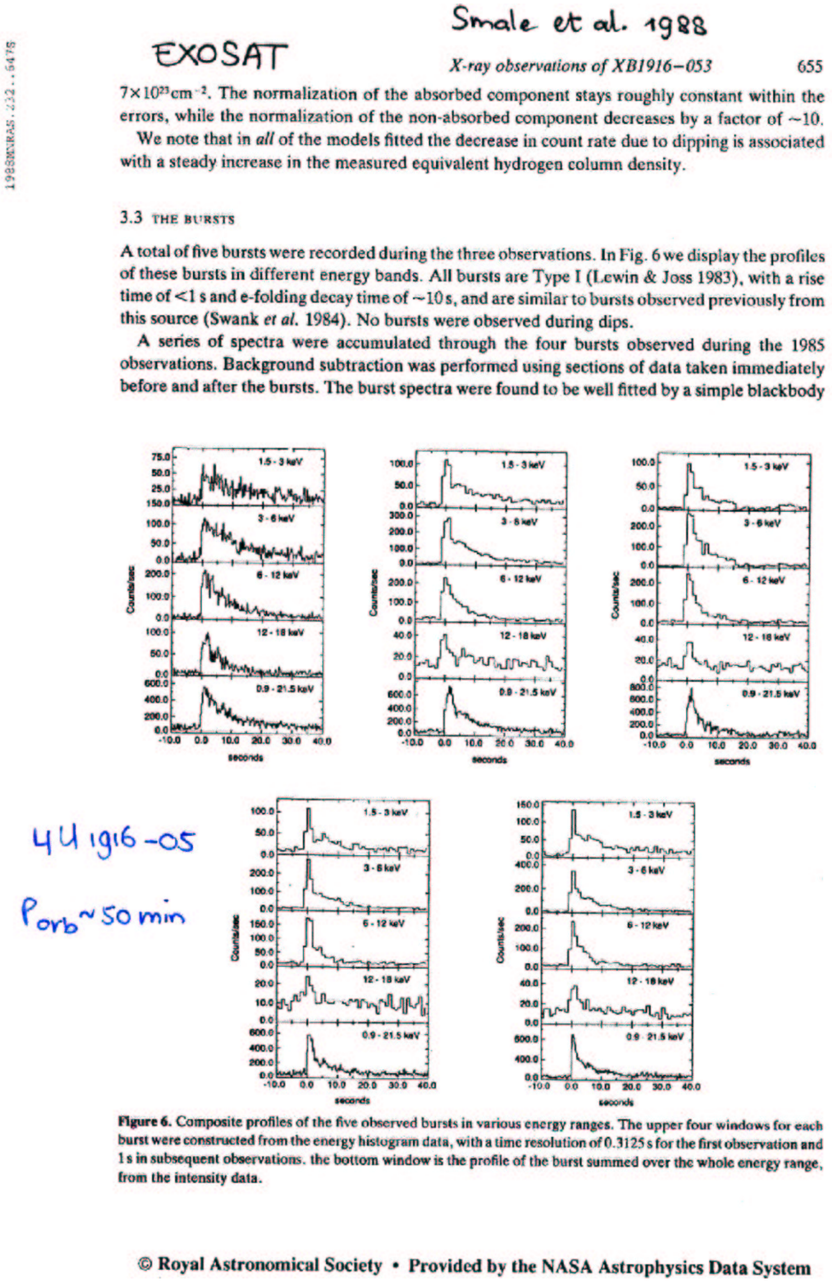


Strohmayer & Brown 2002, ApJ, 566, 1045



Hoffman et al. 1980





Smale et al. 1988

EXOSAT

1988MNRAS.232..647S

X-ray observations of XB1916−053 655

7×10^{23} cm^{-2}. The normalization of the absorbed component stays roughly constant within the errors, while the normalization of the non-absorbed component decreases by a factor of ~10.

We note that in *all* of the models fitted the decrease in count rate due to dipping is associated with a steady increase in the measured equivalent hydrogen column density.

3.3 THE BURSTS

A total of five bursts were recorded during the three observations. In Fig. 6 we display the profiles of these bursts in different energy bands. All bursts are Type I (Lewin & Joss 1983), with a rise time of <1 s and e-folding decay time of ~10 s, and are similar to bursts observed previously from this source (Swank *et al.* 1984). No bursts were observed during dips.

A series of spectra were accumulated through the four bursts observed during the 1985 observations. Background subtraction was performed using sections of data taken immediately before and after the bursts. The burst spectra were found to be well fitted by a simple blackbody

4U 1916-05

Porb~50 min

Figure 6. Composite profiles of the five observed bursts in various energy ranges. The upper four windows for each burst were constructed from the energy histogram data, with a time resolution of 0.3125 s for the first observation and 1 s in subsequent observations. the bottom window is the profile of the burst summed over the whole energy range, from the intensity data.

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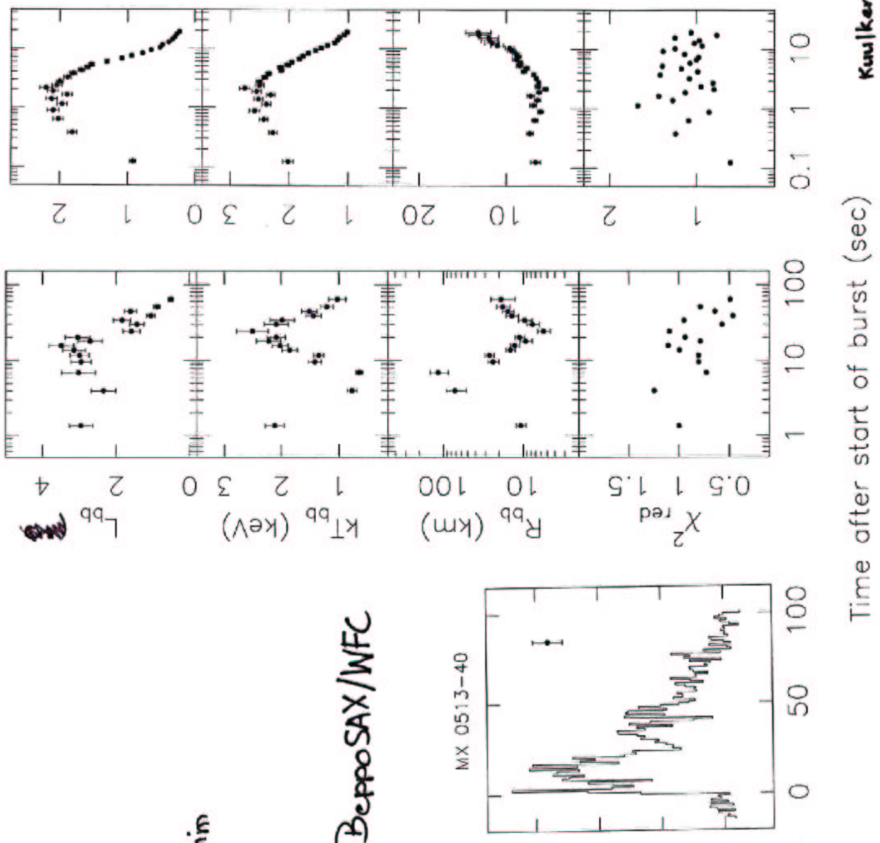
RXTE/PCA

Kuulkers et al. 2003

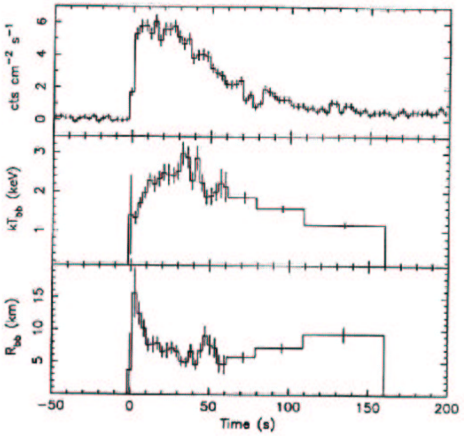


BeppoSAX/WFC

Porb ≲ 80 min

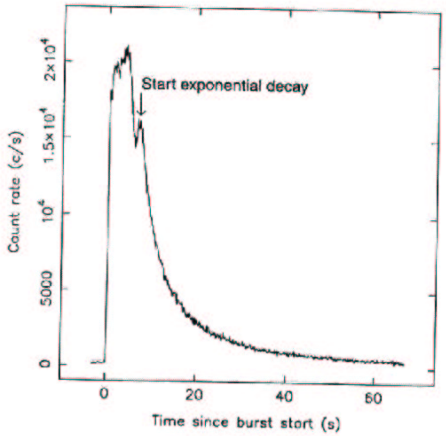
2S 0918-549

BeppoSAX/WFC



Cornelisse et al. 2002

RXTE/PCA



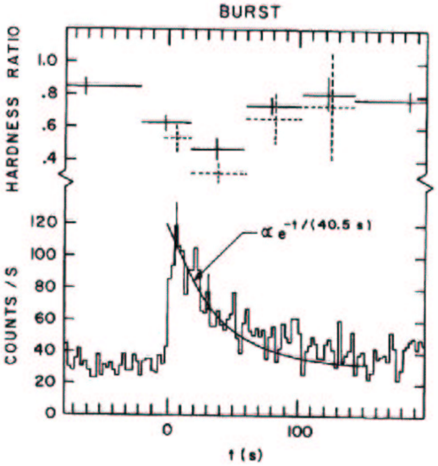
Jonker et al. 2001

↑

Porb ≲ 80 min

↓

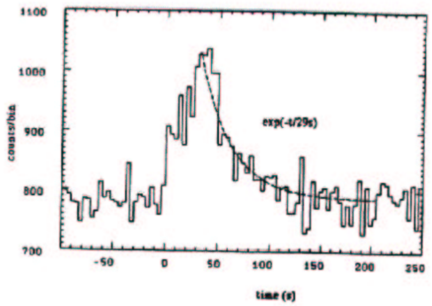
OSO-8



Swank et al. 1978

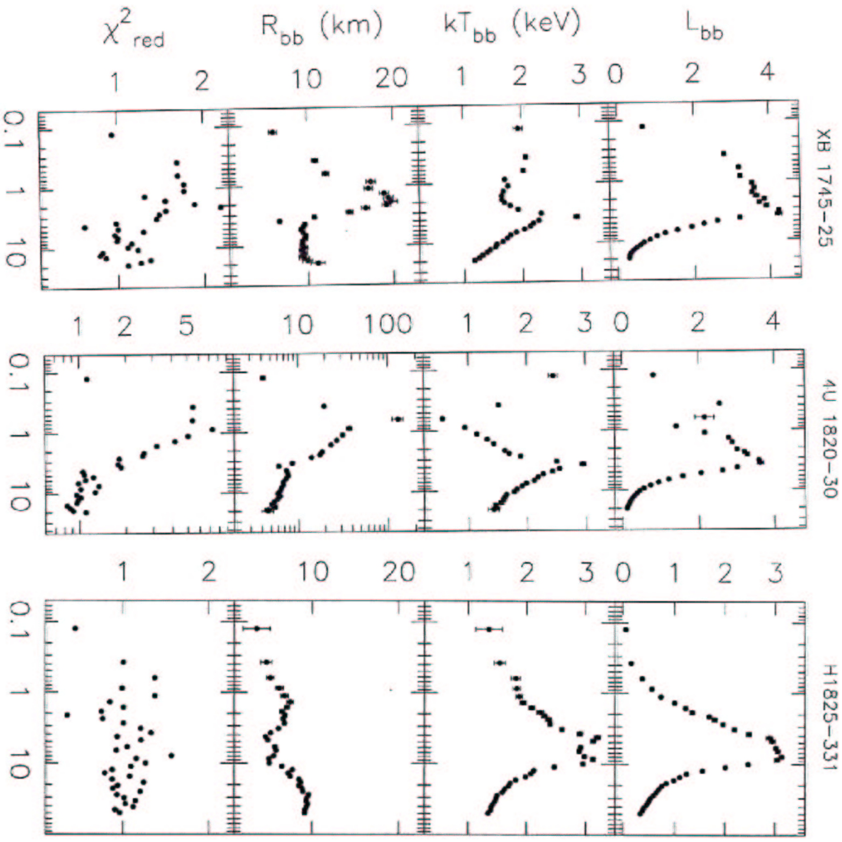
4U0614+091

GRANAT/WATCH



Brandt et al. 1992

RXTE/PCA



Kuulkers et al. 2003

UCSBs

Source	P_{orb} (min)	exp. decay time (s)	longest duration (s)	shortest recurrence time (hr)	F_{peak}/F_{pers}
4U 1820-30	11	~5	~25	~3	~50
A1850-08	21	...	~100	~7	...
4U 1916-05	50	~10	~25	~4	~100
MX0513-40	$\lesssim$80	...	~100	...	... ~~~200~~
4U 0614+091	$\lesssim$80	~40	$\gtrsim$200	?	~200
2S 0918-549	$\lesssim$80	~50	~150	?	~100
H1825-331	55 or 132?	...	~100	...	...
XB 1745-25	25−240 ?	...	~25	...	...

... = to be done

Conclusions:

- X-ray bursts rule out C-O donor (unless spallation of C,N,O → H,He)
  see Juett et al. 2001

- $L_{\rm peak}$ radius expansion bursts NOT a good tracer of donor composition:
  - A1850-08, MX 0513-40
    Long $\underset{\rightarrow H}{\text{X-ray burst}}$ & $L_{\rm peak} \simeq \underset{\rightarrow He}{L_{\rm Edd,He}}$
  - Other example 4U 1636-53 ($P_{\rm orb} = 3.8$ hr)
    optical spectra: H-rich donor
    radius expansion bursts: $L_{\rm peak} \begin{array}{l} \nearrow L_{\rm Edd,H} \\ \searrow L_{\rm Edd,He} \end{array}$

  → H-rich envelope ejected (Sugimoto et al 1984)

- A1850-08, 4U 0614+091, 2S 0918-549, H 1825-331:
  Long X-ray bursts (~100-150 s)
  → H present

  Consistent with conclusions of Podsiadlowski et al. 2002: small residual H content in UCSBs

- 4U1820-30, 4U1916-05, XB1745-25: short